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OUTDOOR CONCENTRATIONS OF THE EQUILIBRIUM-EQUIVALENT DECAY PRODUCTS OF ^{222}Rn IN THE NETHERLANDS AND THE EFFECT OF METEOROLOGICAL VARIABLES

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Abstract — Airborne radioactivity monitors put up in a network as a warning system in case of nuclear accidents were used to gain insight in the temporal variations of ^{222}Rn and its decay products. Average equilibrium equivalent decay product concentrations (EEDCs) over a period of five years for stations across the country range from 1 to 3 Bq.m^{-3}. Hourly averaged concentrations show a diurnal variation at all stations. The amplitude of this variation is maximal in summer and minimal or non-existent in winter. Superimposed is a seasonal variation with a maximum in late autumn and a minimum in spring. Wind velocity appears to be the major variable controlling the variation in EEDC in the outdoor environment of the Netherlands. Humidity seems to be correlated with the EEDC of ^{222}Rn, probably because, due to plateout, a better equilibrium between ^{222}Rn and its decay products is installed. Reduced EEDC during and shortly after rainfall seems to indicate a dilution of ^{222}Rn in ground surface air due to enhanced vertical mixing below the rain cloud.

INTRODUCTION

After the Chernobyl accident, a radioactivity monitoring network was developed and put up in the Netherlands, as in several other countries, as a warning system in case of nuclear accidents[1]. Besides costing a considerable amount of money and hopefully not needed for accidents, this network does generate an overwhelming amount of data on the natural radiation environment. To examine these data a research programme with the following three objectives was launched:

(1) to explain several natural and human-induced phenomena detected by the network;
(2) to reduce the detection limit of the equipment by subtracting the natural background; and, last but not least,
(3) to devise a time-resolved description of the natural radiation environment.

In an earlier paper the use of this National Radioactivity Monitoring network (NRM) was established for time-resolved monitoring of outdoor natural radiation levels[2]. In the present paper some results will be shown on the airborne radioactivity dominated by ^{222}Rn and its short-lived decay products ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po.

In the following sections the results of an analysis of the measured concentrations of airborne decay products of ^{222}Rn, or the equilibrium-equivalent decay product concentration of ^{222}Rn (EEDC), will be discussed. In earlier ^{222}Rn studies[3,4] in the Netherlands average concentrations were measured throughout the country using passive dosemeters, or local variations were examined[5]. However, most of the research on radon in the Netherlands was (and still is) aimed at the indoor environment. In several other countries single-measurement series were performed, sometimes resulting in information on diurnal variations or various seasonal variations of the average ^{222}Rn concentration[6–9]. Results, from hourly to monthly averaged, were often presented at different time resolutions.

In this study average results are presented on the basis of a steady flow of data measured at 14 locations in the NRM network for a period of several years. In two earlier papers[1,2] this network was described in more detail as well as the possibilities of using it for detection of the natural background radiation. This paper focuses on the resulting temporal variations in the EEDC at one specific site (Bilthoven (627)) but, if illustrative, information on other sites will be used as well. Average results are presented for all 14 NRM sites equipped with an airborne radioactivity monitor (NRM principal stations).

After a description of the measurement sites an example of the typical variation observed in EEDC across several sites is given. The succeeding sections present the average and long-term variations in EEDC, compiled from hourly values and several temporal effects (diurnal and seasonal cycles) which are superimposed. These temporal variations in EEDC and ^{222}Rn concentration are ascribed to several meteorological variables. These include wind direction, rain, vertical mixing in the atmosphere (for a review, see, for example a paper by Gesell[6]) and several other variables affecting the exhalation of radon from soil[10,11], the major source of this noble gas. The following sections will discuss several of these meteorological variables as well as soil type and the influence of the variables on the average and dynamic EEDC.

INSTRUMENTATION

Measurement procedure

The NRM consists of 58 measurement stations in all[1]. At all these locations ambient dose rate is recorded using a proportional counter. Concentrations of gross α/β activity are recorded at 14 principal stations using a FAG FHT59S detection system[12] on a continuous basis. Air is sampled at a rate of 10 $m^3.h^{-1}$ during 10 min periods, and particles and aerosols are collected on a tape in front of a lead-shielded ZnS/ plastic scintillator system. The tape is moved stepwise every 10 min, so measured concentrations are related to 10 min averages. A closer study[13] revealed the possibility of converting the natural gross α activity readings to the EEDC of ^{222}Rn. This conversion seems to be independent of the current equilibrium factor and values of EEDC may therefore be determined with a total uncertainty of only 20–25% (95% confidence interval). Because of the relatively large air flow, the detection limit is in the order of 0.1 $Bq.m^{-3}$ EEDC[13].

Because the air inlet of the FHT59S is located 5 m above ground level and because of the relatively short half-life, concentrations of another isotope of radon, ^{220}Rn, and its decay products affect the recorded α radiation and with it the EEDC of ^{222}Rn only to a small degree. During normal operation the recorded NRM data are sent automatically to a central database every hour.

Data on meteorological variables were obtained from several meteorological stations of the Royal Netherlands Meteorological Institute (KNMI) located near the NRM stations. At the Bilthoven location several variables (especially rain) were also measured at the site of the NRM station. For this use was made of a Rotronic weather station, equipped with several instruments (e.g. barometer, thermometer, a ‘tipping bucket’ rainfall monitor) connected to a data logger from Delta-T Devices. Data series were analysed using the statistical computer package MINITAB[14].

Site description

The NRM Bilthoven (627) station is centrally located in the Netherlands at the border of a small town, not far from the city of Utrecht, next to a pasture and in the vicinity of some woodlands to the east. The soil consists mainly of aeolian sand deposits with typical ^{226}Ra concentrations of 10–15 $Bq.kg^{-1}$ in the upper soil layer[15]. ^{226}Ra concentrations in soil for all these locations, and in soils in the Netherlands in general, are fairly average, registering ^{226}Ra concentrations of 20–50 $Bq.kg^{-1}$. All stations but one are situated in rather flat country, i.e. there are no hills or mountains nearby. Only Wijnandsrade (133), in the southern part of the Netherlands, is situated in a small shallow valley.

Data from the Royal Netherlands Meteorological Institute (KNMI) show that: (i) predominant winds at or near all NRM stations come from the southwest, (ii) average wind speeds are more site-specific, and (iii) rainfall occurs predominantly with westerly winds (North Sea and Atlantic Ocean), the maximum occurring with wind from the southwest.

AVERAGED EEDC AND VARIATIONS

Average and long-term concentrations

The average EEDC for ^{222}Rn (about 1.7 $Bq.m^{-3}$ over the period 1990–1995) measured at all NRM principal stations in the Netherlands is rather low (see Figure 1), although not exceptional for a coastal region[7]. The average value in the Netherlands for ^{222}Rn of 3 $Bq.m^{-3}$ (equal to about 2 $Bq.m^{-3}$ EEDC, assuming a constant equilibrium factor, $E_p = 0.7$[7,16]) was measured during an earlier survey[3] using passive radon dosemeters. This average is somewhat higher but in rather good agreement with the data (Figure 1), especially if one considers the uncertainty (2σ) in both measurement methods at these low concentrations: 20–25% for the NRM FAG monitors and some 70% using the passive dosemeters at outdoor concentration levels[17]. Furthermore, the recordings of the NRM at 5 m above ground might on average even be somewhat smaller[6] than those of the survey conducted at about a 1 m height. This is due to a slow decrease in radon concentration with height. Average EEDCs measured above land are in the range of 1–10 $Bq.m^{-3}$[7]. Due to the low ^{222}Rn content of marine air (normal range in marine air is about 0.001–0.1 $Bq.m^{-3}$[7]) and the predominant sea

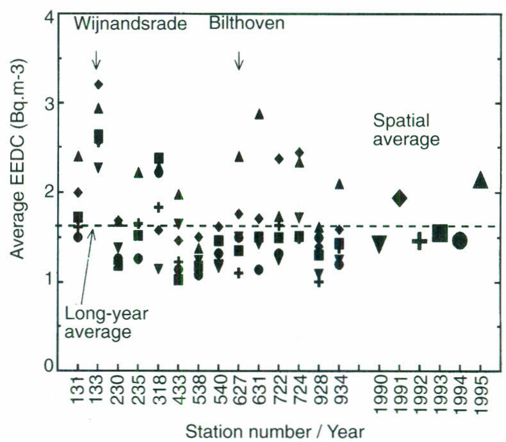

Figure 1. Annual variations for ^{222}Rn EEDC at all NRM locations for the years 1990 through 1995 as well as spatially averaged values for those years.

breeze in the Netherlands, the yearly averaged concentration is expected to be lower than at locations more inland (e.g. Germany) where even marine air will have picked up some radon. Yearly variations over the six years, 1990–1995, amount to about 15% (one standard deviation) for most of the stations, up to 25% for Braakman (318), Eibergen (722) and Wageningen (724) stations (see Figure 1), due to 'high' values for 1991. No clear trend was detected in the six years of operation of the network, although on average the EEDC was somewhat higher in 1991 and 1995.

Although yearly averaged EEDCs are rather constant, the frequency distribution of hourly averaged data (Figure 2) indicates a large variation in time. All distributions may be represented by a similar log-normal or simple exponential function, at least for concentrations up to 5 Bq.m^{-3}. This confirms that the EEDC is determined by a number of (meteorological) parameters, not just by the soil underneath the station, since in that case the concentration in surface air would be a simple linear function of the fairly constant local exhalation rate of radon from soil. The median concentration is in all cases about 60% of the mean value. At higher concentrations the distribution has been underestimated using a simple exponential function. Although these rare high concentrations show rather large uncertainties on the right side of the distribution, the frequencies exhibit a clear tendency to higher values. At several stations, especially those situated near the coast (like Wieringerwerf (538), Figure 2), the distribution decreases somewhat faster with concentration than that at stations situated more inland.

Diurnal variations

The diurnal variations of the radon EEDC were analysed for the 1990–1993 period. In Figure 3 the hourly averaged values are presented for the Bilthoven (627) location. It is clear that from March through November the average EEDC rises in the early morning hours and drops in the afternoon. During the summer months this effect is maximal and in the autumn it again diminishes. This diurnal variation was found earlier by other authors[6]. The variation was thought[18] to be linked to the stability of the atmosphere. During the night, a stable inversion layer — *the temperature rises with altitude up to several metres and then declines with a further increase in height* — often develops above the ground. This results in a much reduced vertical mixing in the lower atmosphere. ^{222}Rn exhaled from the soil will therefore be confined to this thin surface layer and consequently lead to higher concentrations during the night. After dawn sunlight will warm the lower atmosphere and the inversion layer will disappear. This process will be more pronounced during the summer months than during winter for two reasons:

(i) during the winter months stable conditions during

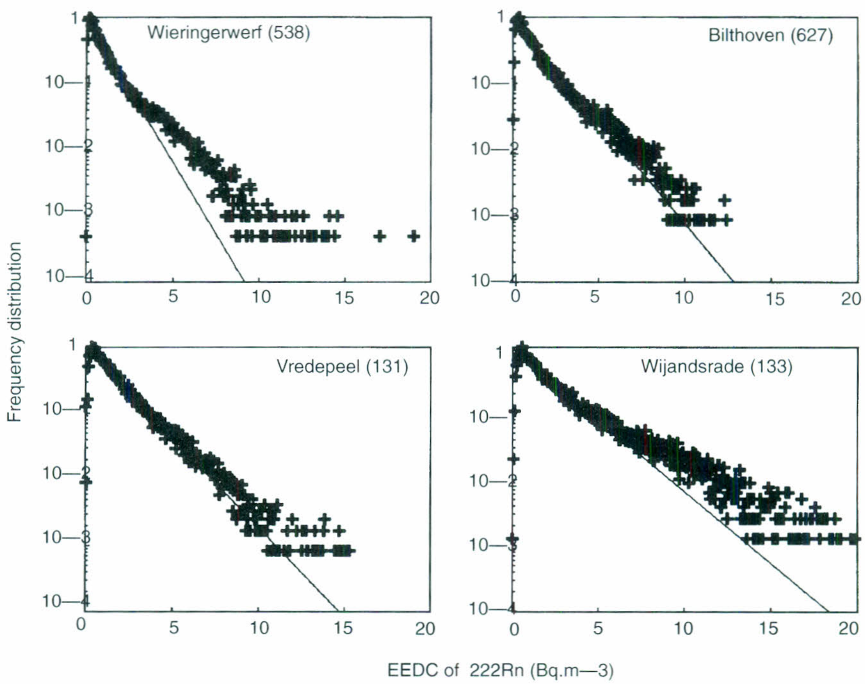

Figure 2. Frequency distributions of hourly averaged EEDC values at four NRM stations (data for 1990–1993), along with exponential fits (solid lines).

the night occur less often than in summer (the average wind velocity at night at the De Bilt location, for instance, is twice as much during winter than during summer) and

(ii) the radiation from the sun during summer is far more intense than during winter, resulting in a significantly higher warming of the soil and air near the ground surface in summer.

Another remarkable detail is the shift in time for which the maximum average concentration occurs. During the month of June (long days), the maximum concentration occurs several hours earlier than in late autumn or early spring (data are for Universal Time, UT, so this is no summer time effect). This shift is typically associated with dawn. Another observation to be made is the increase in daily averaged EEDC over the months, with a maximum in November. This effect seems to be seasonal.

The Bilthoven location is illustrative for most of the NRM locations. In summer, the variation between night maximum and day minimum is on average a factor of 2–3. During winter, average concentrations during day and night are similar. However, Wijnandsrade (133) behaves in a somewhat more pronounced way (up to a factor of 6 during summer). As was previously found (Figure 1), this station also has the highest average EEDC values in the NRM, may be because it is located in a small valley, so that there is only a very thin stable layer in the (summer) evening. This 'valley effect' is also reported by others[9]. Especially in a shallow valley this inversion layer may be only a few metres thick, resulting in built up concentrations of ^{222}Rn and its decay products that are sometimes orders of magnitude higher than during the afternoon during turbulent mixing conditions[6,8,9,18,19]. The variations found at all locations are very similar to those published by Hötzl and Winkler[9] for a location near Munich, Germany. They found values, however, that are on average 9 Bq.m^{-3} EEDC, considered proper for continental locations.

Seasonal variations

As already observed in Figure 3 there is a seasonal effect. Figure 4 presents the monthly averaged EEDC values of all 14 NRM principal stations. The results for Bilthoven (627) are again typical for all NRM stations, except for Wijnandsrade (133). A minimum is observed from spring to early summer, followed by a considerable increase (factor 2–3) until November. In winter and

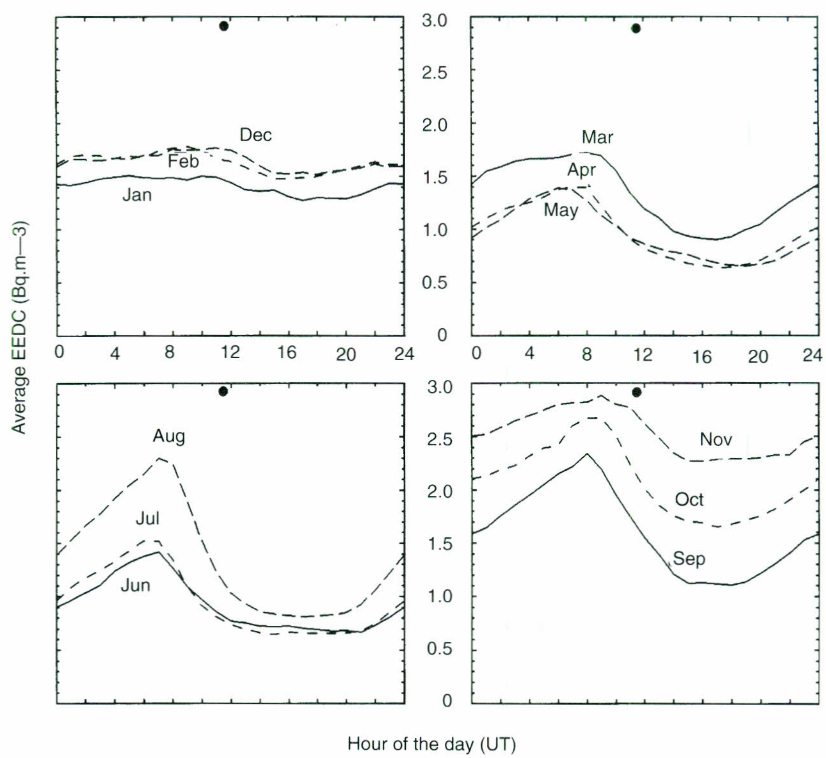

Figure 3. Daily variation in the hourly averaged EEDC values at the Bilthoven location, presented for all 12 months (data 1990–1993). Dots indicate local noon.

early spring the EEDC value drops again. The maximum to minimum ratio is about 2.5. Seasonal effects, also known from other studies[6,9], are attributed to regional meteorological conditions, e.g. horizontal and vertical mixing in the atmosphere, ambient temperature and humidity.

METEOROLOGICAL VARIABLES AND EEDC

The main source of radon is the soil. However, several meteorological variables affect the radon concentration in outdoor air. After exhalation from soil the gas ^{222}Rn and its short-lived decay products are transported vertically (mixed) in the boundary layer and dispersed horizontally due to wind. This last process is dominated by wind speed and direction. The decay products may be removed from the air due to dry and wet deposition. In this process humidity of the air and rainfall play an important part. Another variable, atmospheric pressure, is believed to be important in the dynamics of the exhalation process and may therefore affect the EEDC in surface air. And last but not least, soil type, i.e. physical quantities such as porosity, particle diameter and water content, is not just an indicator for ambient dose rate due to photons but also for the exhalation rate of ^{222}Rn and thus the EEDC in surface air. In this section the influence of these quantities on EEDC, as measured by the NRM is discussed.

Wind speed and direction

The radon concentration at a particular location is influenced by two effects: (i) radon produced locally (depending on soil type and vertical mixing conditions) and (ii) radon transported from other locations. For the latter, the distances that may be bridged during a half-life time of 3.8 days (^{222}Rn) are considerable.

It is clear that wind indicates moving air. EEDCs of ^{222}Rn recorded at the various NRM stations may therefore be a signature of air masses transported from other regions. If interested in the local environment (for instance, local ^{222}Rn emanation and exhalation), one should select only those situations where there is no wind. Wind direction and speed determine the influence of radon exhaled from soil in more remote regions. To study the effects the EEDC data were sorted for five wind speed classes and 36 angles (of 10° each).

Results for wind speeds of 0.5–2 m.s^{-1} are presented in Figure 5 for all NRM stations and for all speeds for the stations Bilthoven (627) and Wijnandsrade (133) in Figure 6. It is clear from both figures that, on average, relatively high concentrations of radon are present in the air coming from the southeast, i.e. the European continent. In contrast, concentrations decrease considerably with northwest winds. This is due to the radon-poor marine air coming in from over the North Sea and the North Atlantic. However, large differences still exist

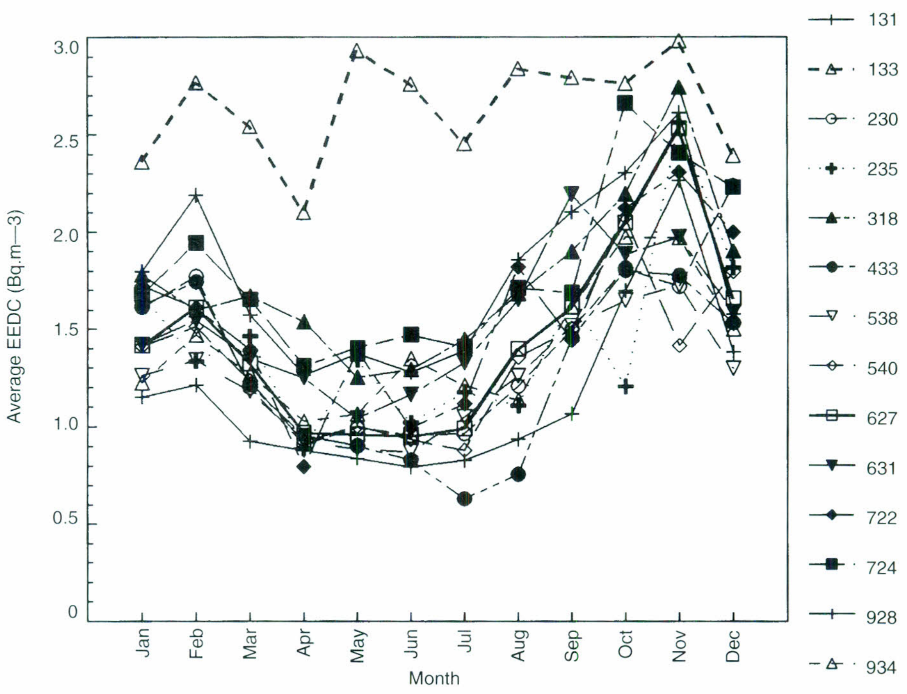

Figure 4. Seasonal variation of monthly averaged EEDC values at all 14 principal NRM measurement stations (data 1990–1993).

between all the different stations, probably due to the local environments. Figure 6 also shows that for low wind speeds the recorded value of EEDC becomes less dependent on wind direction. The measured EEDC reflects the concentration due to locally produced radon. For both locations the median EEDC seems to be enhanced if air is coming from the southeast at a low speed. At higher wind speeds median EEDCs tend to decrease for all wind directions. This feature is found for all sites in the NRM network. This is partially due to the well-known effect of strong vertical mixing accompanying strong winds, also called vertical wind-shear, resulting in a dilution of the radon in surface air. Another reason might be that high wind speeds in these regions usually accompany a low pressure area coming in from over the Atlantic. Because the air circulates around such an area, the wind direction is no longer adequate as an indicator of radon source areas (see also section on '*Atmospheric pressure*').

As previously mentioned the prevailing wind direction in the Netherlands is southwest (about 30–50% of the time, depending on location). However, during the autumn and winter seasons, southeastern winds occur more than average, which implies that more continental air masses are imported and thus, higher average radon concentrations in the autumn and winter months. This shift may be parameterised using the median EEDC per wind direction and wind speed class found earlier in Figures 5 and 6:

$$C^{50\%}_{EEDC} = \int_{|\vec{v}|_{min}}^{|\vec{v}|_{max}} \int_{0}^{2\pi} C^{50\%}_{EEDC}(\vec{v})\, f(\vec{v})\, d\phi\, dv \qquad (1)$$

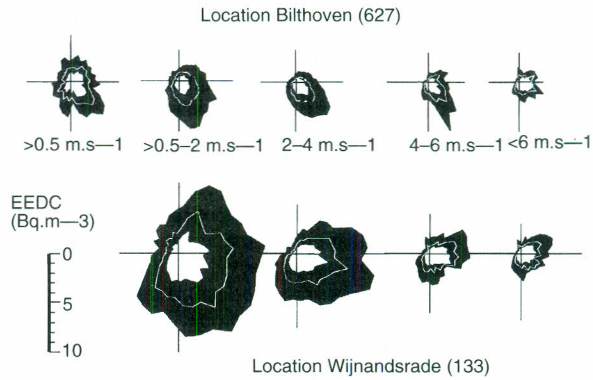

Figure 6. Radon EEDC values per wind direction at five different wind speeds. The white line represents the median while the black area indicates the range between the 1st and 3rd quartiles.

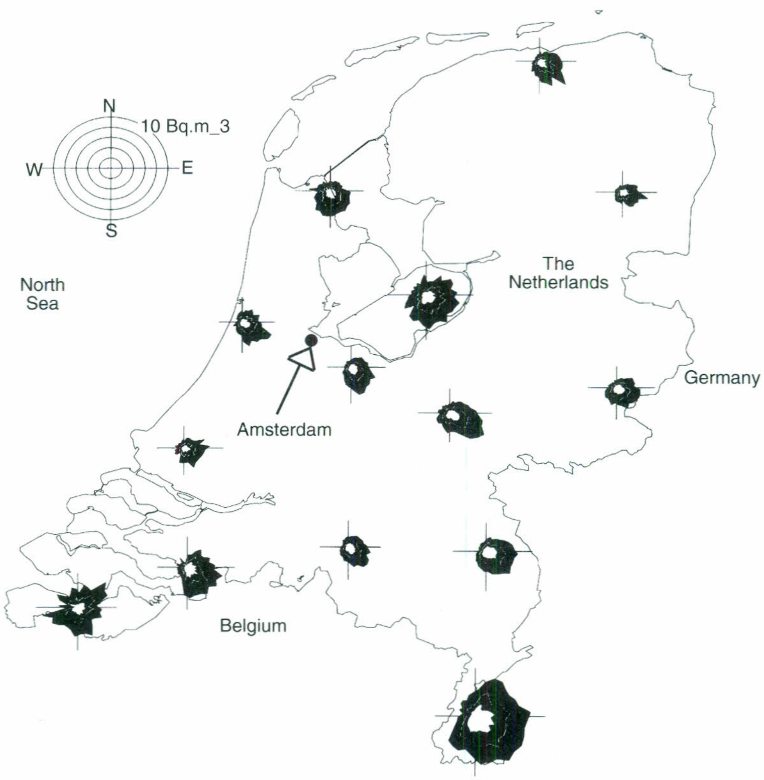

Figure 5. EEDC per (local) wind direction at a wind speed of 0.5–2 m.s^{-1} for all principal NRM stations. Shown are: median concentration (white lines) and 25–75% data range (black areas).

where the median ($C^{50\%}_{EEDC}$) is compiled from the median concentration per wind speed ($|\vec{v}|$) and direction (ϕ), and the frequency of occurrence of that combination $f(\vec{v})$. An approximation of Equation 1 using discrete median concentrations for the five wind speed classes per 10° angles was used to verify whether wind direction and speed could be used to calculate the observed seasonal variation in EEDC. Figure 7 shows the results for the Bilthoven (627) location along with the monthly median of the observed EEDC. It is clear from the figure that the shift in wind direction during the year is an indicator for the seasonal effect found in the previous section. It also explains why concentrations recorded at Wijnandsrade (133) do not seem to be seasonally dependent (see Figure 4). The valley in which this station is situated faces more or less southwest to northeast. Air masses from the southeast are probably diverted to another direction in the valley. This assumption is supported by the observation that at higher wind speeds, the EEDC is higher for air masses coming from east-northeast (Figure 6), while at all other NRM stations the average EEDC for all wind speeds is highest for southeastern air masses.

Humidity

In atmospheric air the short-lived decay products of ^{222}Rn rapidly attach to aerosols. Furthermore, cloud droplets form through condensation around these aerosols. If the amount of water in the lower atmosphere, or in short, the humidity, increases, the number of droplets formed during condensation also increases. The concentration of attached radon decay products in air is therefore expected to rise with humidity. This indicates that ^{222}Rn and its decay products should be in better equilibrium at higher humidites, thereby raising the EEDC for a constant ^{222}Rn concentration. Furthermore, humidity, like clouds, restrains the back radiation from soil and was indeed found[18] to be a quantity opposing the formation of an inversion layer near the ground, and thus high radon concentrations during the night[18]. Figure 8 demonstrates the effect of humidity ($g.m^{-3}$) of surface air on EEDC at the Bilthoven (627) location. Temperature inversions at night near the ground surface result in the build-up of radon and its decay products. To avoid confounding factors the data have therefore been selected for daytime (10^{00}–16^{00} UT) only. From Figure 8 it is seen that EEDC and humidity are indeed positively correlated. Furthermore, the EEDC in surface air can be approximated by EEDC = Constant + 0.007 $\times$ (humidity)^2 (see Figure 8) up to almost 3 $Bq.m^{-3}$, which is twice the yearly averaged EEDC at the Bilthoven location (1.5 $Bq.m^{-3}$). A possible explanation for this square dependence on humidity might be a kind of surface effect caused by deposition of unattached radon decay products to small water droplets.

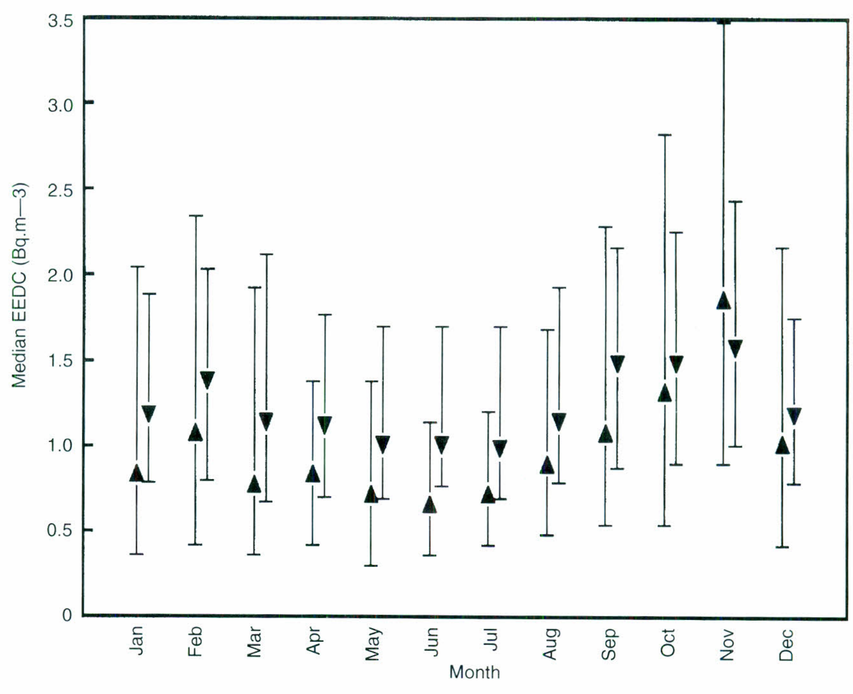

Figure 7. Seasonal variation of hourly data (▲) and an hourly parameterisation (▼) of median EEDC in Bilthoven (627), 1990–1993. The bars indicate the 25–75 percentiles.

Rainfall

During rainfall or other forms of deposition, part of the decay product activity fixed in the clouds is washed out, implying that the EEDC measured at the ground level would not be affected by rain. However, measurements show that at least during and shortly after rain events with southeasterly winds (i.e. continental air), the EEDC is reduced by about 30–50% (significant at the 99.99% confidence level). In Figure 9 data are given for three stations. The largest effect is seen for Wijnandsrade (133), where EEDC is significantly reduced for rain clouds coming from all four directions presented in the figure. At the other two stations, especially Wieringerwerf (538), EEDC is reduced significantly but only during rain from the southeast and southwest. Although one might think that this phenomenon is due to rainout of decay products of ^{222}Rn, this process is thought to be not important. The decay products are collected on aerosols with a typical diameter of 0.1–0.5 μm[20], which have a low scavenging rate by rain drops[21]. ^{222}Rn itself is not expected to wash out either, because of its low solubility in water. The explanation might then be that during the formation of a rain cloud (strong) vertical mixing occurs in the boundary layer just below the cloud, thereby reducing the EEDC measured near the ground surface. If these clouds are produced above the sea this reduction effect is less important because marine air is already low in radon concentration. Furthermore, during transport across the land the marine air will be slowly enriched with ^{222}Rn from soil (Figure 10). This reduction or dilution due to vertical mixing even depends on the amount of rainfall (Figure 11), which may be explained by stronger vertical mixing during or shortly after heavy rainfall than during or shortly after a slight drizzle.

Atmospheric pressure

Atmospheric pressure itself is not a controlling variable of radon transport, but indicates the source of air masses. Although ^{222}Rn exhalation variations amounting to a factor of 2 have been associated[10,22] with pressure changes, these changes are relatively small compared to the variations that result from vertical exchange processes[23]. High pressure in the Netherlands usually coincides with continental air and thus high EEDC values (see section on '*Wind direction*'). This is in contrast to low pressure fields, which usually indicate oceanic air. These effects can be observed in Figure 12. For air from the southeast, EEDC increases slightly with increasing atmospheric pressure. This increase is not so much correlated with atmospheric pressure as with wind velocity. High wind speeds, as a rule, coincide with low pressure fields (Figure 13) and vertical mixing or insta-

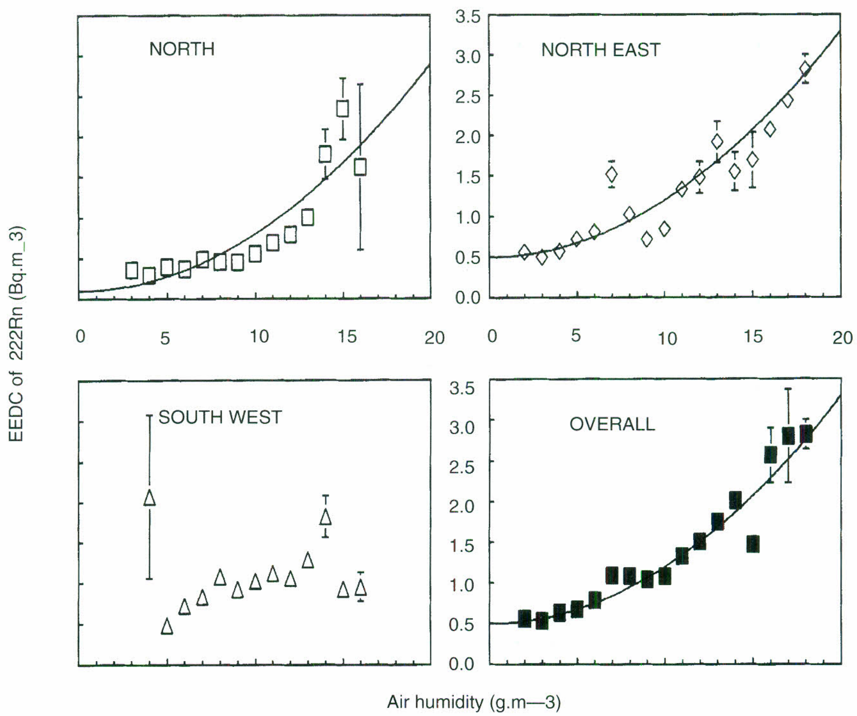

Figure 8. Average EEDC plotted against humidity (g.m^{-3}) at Bilthoven (627) station for SW (Δ), NE (◇) and N (□) winds, and averaged over all directions (■), including quadratical fits.

bility of the lower atmosphere, as previously stated, is highest during strong winds, thereby reducing the EEDC at ground surface.

Soil type and EEDC

The differences found in EEDC between the locations, Bilthoven (627) and Wijnandsrade (133) and the yearly averaged concentrations found earlier (Figure 1) have already hinted at the variation in concentration among sites. Besides the meteorological variables, soil type is an important quantity in determining the average EEDC, especially on the local scale. However, to correlate the EEDC positively, as measured by the NRM principal stations, with soil type, it is necessary to select only data during windstill weather conditions. The hourly data on wind speed from nearby weather stations were used to make selections from the complete NRM data set. The result is shown in Table 1. The average EEDC values for calm weather conditions are all higher than the average values given for all weather conditions, which is fairly typical for coastal regions with a predominant seawind. There is a possible correlation with soil type, i.e. higher values over river and calciferous marine clay, and loess and lower values over more sandy soils (see Table 1). To check whether a correlation exists between long-term averaged terrestrial ambient dose rate (and thus soil type) and EEDC during wind-calm periods, see results in Figure 14. This figure shows clearly that where EEDC is averaged over all occurring wind velocities, no significant correlation exists between EEDC and ambient dose rate. However, if only data for wind-calm periods are selected, a weak correlation may be observed. At least two important factors affect this correlation:

(i) the concentration ratio of ^{226}Ra, and radionuclides of the ^{232}Th series and ^{40}K, is not constant for different soils (i.e. different ambient dose rates may accompany the same EEDC); and
(ii) the emanation, transport and exhalation of ^{222}Rn in and from soil varies with soil type (i.e. soils with the same dose rate above ground surface may exhale different amounts of ^{222}Rn and thus give rise to different EEDC data).

These factors cause a spread in the data along the ambient dose rate axis as well as the EEDC axis.

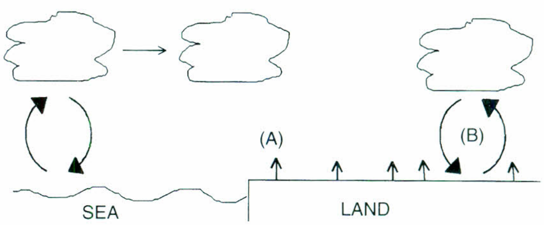

Figure 10. Schematic representation of enrichment (A) of radon-poor marine air and dilution (B) of radon rich continental air.

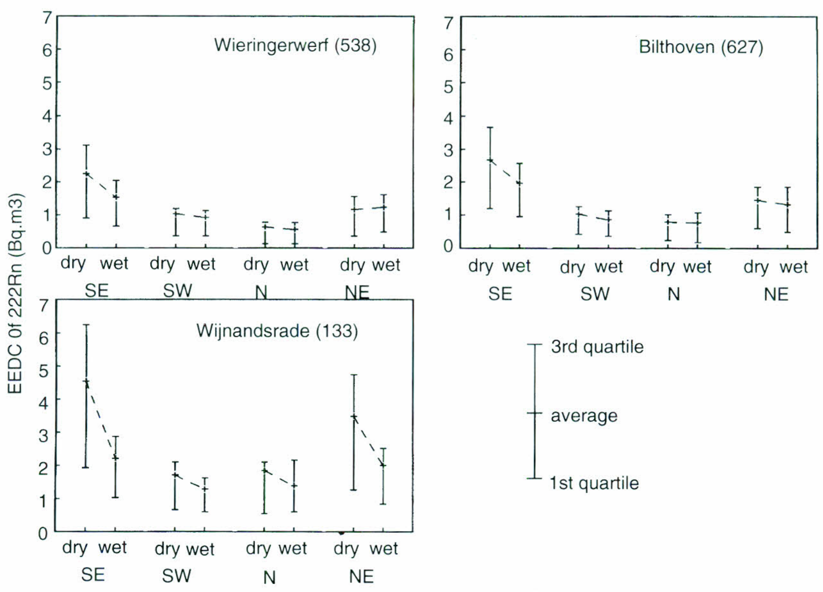

Figure 9. Reduction of EEDC observed during rainfall at three stations. In most cases the decrease is significant at the 99.9% confidence level.

CONCLUSIONS AND DISCUSSION

The NRM is very suitable for measuring the time-resolved EEDC. Results are in line with measurements made with more ‘appropriate’, i.e. radon detectors[9]. The research results presented here indicate a relatively low average EEDC of about 1.7 Bq.m^{-3}, for ^{222}Rn in the outdoor environment of the Netherlands, although fairly typical for coastal areas and in line with results from an earlier survey[3] using passive dosemeter techniques.

Furthermore, two major periodical variations in the EEDC are found: (i) a diurnal variation, which is strongest during summer and almost non-existent during winter, and (ii) a seasonal variation with a maximum in late autumn and a minimum in spring. Strong correlations between wind direction and speed, on the one hand, and ^{222}Rn (progeny), on the other, are found in the Netherlands. During periods of high wind velocities, the measured EEDC is reduced, probably caused by vertical mixing through windshear. A possible explanation is found for the seasonal variation in radon concentration: a slight shift in average wind direction during the season. This shift results in relatively more continental air during winter and more air from the ocean during spring.

Attachment of decay products of ^{222}Rn is found to be correlated to the amount of water in the air. Average EEDC increases quadratically with the absolute humidity of the air. At high humidities the EEDC is almost twice the yearly averaged concentration. Absolute humidity might be an important indicator of the equilib-

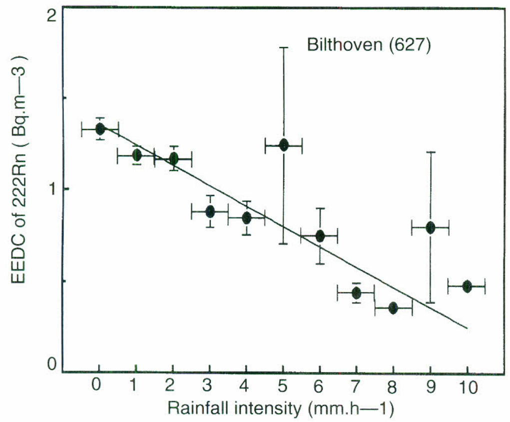

Figure 11. Dilution of EEDC in surface air for various rainfall intensities. Vertical error bars indicate error in the mean; horizontal bars indicate step size (data: 1990–1993).

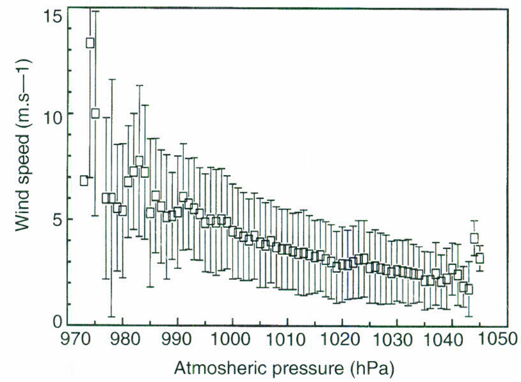

Figure 13. Average wind speed plotted against atmospheric pressure (error bar is $\pm 1\sigma$) at a station of the Royal Netherlands Meteorological Institute in De Bilt (near Bilthoven (627)).

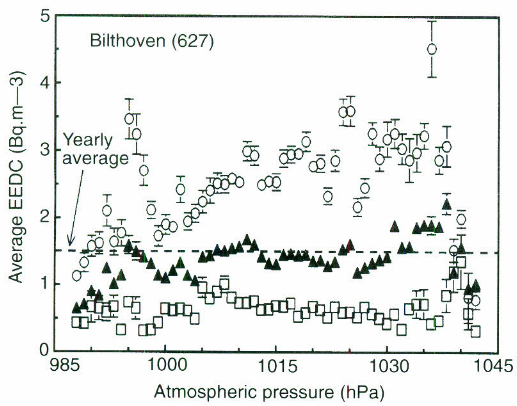

Figure 12. Average radon EEDC (standard error in mean) as a function of atmospheric pressure (hPa) at the NRM station at Bilthoven. Data are given for SE winds (○; continental), and NW winds (□; marine) as well as for all wind directions combined (▲) (data: 1990–1993).

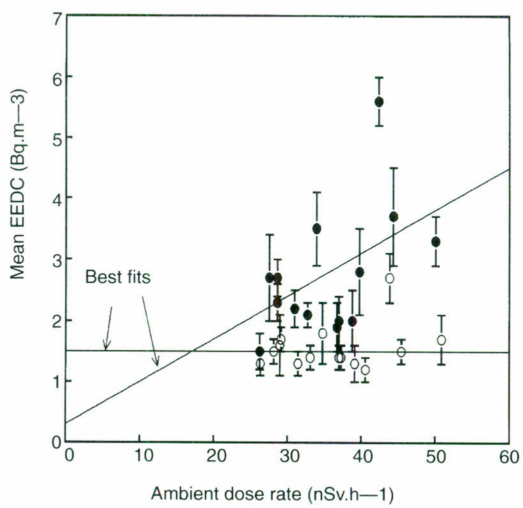

Figure 14. Mean EEDC plotted against ambient dose rate for all principal stations. Data (1990–1993) for all wind speeds (○) and for v < 0.5 m.s^{-1} (●).

rium factor, but more research using methods to measure ^{222}Rn gas simultaneously is needed to substantiate this factor as a function of time.

The EEDC in surface air is found to be reduced during rainfall and is roughly inversely proportional to the rain intensity. This feature cannot be fully understood from washout or rainout processes. It is suggested that during cloud formation a relatively strong vertical mixing occurs right under the cloud, which reduces the EEDC at the surface.

Last but not least, a slight correlation is found between the time-averaged EEDC or radon in surface air on the one hand and ambient dose rate on the other. This correlation is only found during periods of wind-calm weather and is an indication of the exhalation rate of ^{222}Rn from local soil.

An advantage of a network like the NRM is that data at all locations are recorded simultaneously with identical detectors. These data, together with several meteorological variables recorded at weather stations nearby, may be used for validating air dispersion models. This makes it feasible to validate results from a dynamic transport model of ^{222}Rn.

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Table 1. Average EEDCs ($\pm 1\sigma$) for all NRM principal stations compared with mean values for wind calm periods only. Data are based on hourly measurements in the period 1990 through 1993.

NRM location (no)	Mean EEDC ($Bq.m^{-3}$)	Mean EEDC ($Bq.m^{-3}$) (windspd <= 0.5 $m.s^{-1}$)	Soil type
Vredepeel (131)	1.7 (±0.2)	2.7 (±0.3)	Sandy (non-calciferous)
Wijnandsrade (133)	2.7 (±0.4)	5.6 (±0.4)	Loess
Houtakker (230)	1.3 (±0.2)	2.2 (±0.3)	Sandy (non-calciferous)
Huijbergen (235)	1.5 (±0.2)	2.7 (±0.7)	Sandy clay
Braakman (318)	1.8 (±0.5)	3.5 (±0.6)	Calciferous marine clay
Vlaardingen (433)	1.3 (±0.3)	2.0 (±0.5)	Built-up environment
Wieringerwerf (538)	1.2 (±0.2)	2.8 (±0.7)	Calciferous marine clay
Leiduin (540)	1.4 (±0.2)	1.9 (±0.4)	Dune sand
Bilthoven (627)	1.4 (±0.2)	2.1 (±0.2)	Sandy
Biddinghuizen (631)	1.5 (±0.2)	3.7 (±0.8)	Calciferous marine clay
Eibergen (722)	1.6 (±0.5)	2.3 (±0.3)	Sandy
Wageningen (724)	1.7 (±0.4)	3.3 (±0.4)	River clay
Witteveen (928)	1.3 (±0.2)	1.5 (±0.3)	Sandy peat
Kollumerwaard (934)	1.4 (±0.2)	2.0 (±0.4)	Marine clay

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